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(6) DETECTION OF COMBAT SOUNDS BY THE HUMAN EAR

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The importance of the auditory system has long been recognized in connection with speech communication and considerable effort has been directed toward understanding the functional relationships within the auditory system in this regard. In spite of our justifiable interest in speech signals, it is apparent that species other than man have developed exquisitely sensitive auditory systems; this suggests that the survival value of the ear may have rested in its ability to deal with other types of signals and serve as something other than a device for the reception of speech. For example, auditory input allows us to monitor activity in the world around us without requiring at the same time that we turn toward the source of sound. Thus, we remain oriented with respect to what is going on around us and prepared for whatever happens. With the exception of speech communication in a limited number of contexts, we actually know very little about the role of the auditory system in normal behavior, and it goes without saying that we are equally ignorant where performance in operational Army situations is concerned.

There are some data which indicate that the auditory system may play an essential role on the battlefield. For example, a survey conducted after World War II and the Korean conflict showed that the most important target for units in the field was enemy personnel (Katzell, et al., 1952). It was also noted that enemy personnel were most often detected by the sounds they, or their equipment, made. Interviews with Viet Nam veterans indicate a similar finding. For example, the approach of enemy personnel would often be revealed by the noise made in parting dense foliage. There is a certain face validity to these observations, especially when you consider that almost everything we do is accompanied by some noise. There are

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analogous situations in the civilian world which emphasize the same point. Persons with hearing losses may have to give up hunting as a recreation because they can no longer hear the game. The same story with a slightly different outcome involved a poacher who had to give up his 'profession' because he could no longer hear the game warden!

Given the importance of auditory input to the functioning of the soldier on the battlefield and the lack of systematic knowledge regarding the performance of the soldier as it relates to his ability to hear, a comprehensive research effort has been initiated at the Human Engineering Laboratory to investigate and quantify the relationship between the ability to hear and performance in the Army context (Hodge & Mazurczak, 1975). It is anticipated that this effort will ultimately sample the acoustic environments in which performance is expected to occur, as well as examine the performance required in a variety of operational settings. In addition, we expect to include in the analysis the interactions between the acoustic factors associated with the tasks and the capacities of individual ears. Put concisely, we'd like to know what you have to be able to hear in order to perform satisfactorily in the Army and how hearing losses affect this performance.

As an initial step in this program, it was decided to focus on how the ability to hear a complex transient sound (such as that produced by personnel movement) related to traditional measurements of auditory acuity. Once this relationship is established, it would then be possible to use the data on auditory sensitivity already available for Army personnel to make predictions regarding performance in the field. The primary problem encountered was that no standard method existed for analyzing the complex transient sounds. This was true for a variety of reasons, i.e., traditionally the interest has been in the simpler problem of detecting continuous sounds, the techniques for acoustic analysis are only now being developed, speech communication has received primary attention in the past, etc. It was therefore necessary to devise a method for analyzing these sounds that took into account both their transient character and the capacities of the auditory system for handling stimuli of this type. The second step was to test the model derived in the first phase on the detection of combat-relevant sounds and, lastly, we considered the implications of the model for performance in the field.

The details of the analysis program, the instrumentation used and the exact tests procedures followed are, for reasons of economy and completeness of reporting, published elsewhere (Price & Hodge, 1976). The presentation here, therefore, focuses on the rationale for the tests, a general account of the conduct of the experiments, and a discussion of the findings and their implications.

METHOD

Analysis of Complex Transient Sounds

A number of important properties of the auditory system must be taken into account when considering how sounds are detected. Before discussing them, however, we should define the concept of 'detection' as used in this paper, especially since it differs somewhat from common usage. In this paper we distinguish between the concepts of detection and identification of sounds. For detection to occur, it is only necessary that the subject's response indicate that he heard something (in addition to the background noise). Normally, he would have little or no idea what produced the sound, and would only be able to say that he heard a faint sound. On the other hand, identification implies that the subject must not only detect the sound but also be able to single it out as having a distinctive character. For example, as a sound too weak to be heard is raised in intensity, the subject would first say that he heard something but could not say what it was (detection); after the sound had been further increased in intensity he could say that it sounded like someone walking through a puddle (identification). The interval between detection and identification is a gap that should be examined in detail; however, at the moment we can say very little about how much of an increase in intensity is required before it can be identified by normal ears and/or ears that have lost some sensitivity (as in the case of most ears in the Army). This point will be discussed further later in the paper and is mentioned here to explain our interest in first focussing on the somewhat simpler problem of detection before proceeding to the more complex problem of identification.

In developing the detection model, two basic properties of the ear were taken into account. The first was that sensitivity varies as a function of frequency. This necessitated an analysis of each sound of interest with respect to its frequency content, i.e., a Fourier analysis was performed to determine the spectral distribution of the energy. The output of such an analysis is the energy present in a fixed bandwidth across the range of frequencies analyzed. The ear, however, does not appear to respond as a fixed-bandwidth filter; rather, it appears to analyze sounds as though it consisted of a series of 24 'critical bands' spanning the frequency range from 50 Hz to 13,500 Hz. The center frequencies and upper and lower cutoff frequencies have been empirically established for the normal ear (Scharf, 1970); consequently a computer program was structured so that the energy was integrated within each critical band. For most of the auditory range, the critical bands approach 1/3 octave in width.

The second property of the auditory system taken into account was its ability to integrate energy for a period of up to 200 msec. This means, for example, that if a 200 msec tone were just detectable by the ear, then another tone of the same frequency but only 20 msec long would have to be 10 dB more intense in order to be detected. Periods longer than 200 msec produce no additional increase in sensitivity. To account for this property of the auditory system, a Fourier analysis was performed for each 20 msec segment of the sound in order to establish the spectral content present in the shortest practical period. Then, within each critical band, the energy was integrated for 200 msec. Another integration was then performed for 200 msec, but displaced 20 msec in time. This process was repeated all through the duration of the sound, and the 200 msec period with the greatest energy was selected as the one most likely to be detected. These values (critical band and energy) were printout out for use in the prediction of detectability.

This analysis of the stimulus characteristics was performed by means of a hybrid tape-recording/computer analysis described in greater detail elsewhere (Price & Hodge, 1976). The essential elements were that it performed a frequency analysis every 20 msec, combined the results into critical bands, integrated for 200 msec, and then searched to find the 200 msec period containing the most energy.

Determination of the Sensitivity of the Ears

The first half of the problem of detectability, as outlined above, revolved around the character of the sound energy arriving at the ear. The second half of the problem relates to the sensitivity of the ears at which the energy arrives. To allow for this variable in the detection model, pure tone thresholds were measured for each ear. Audiometry was conducted for each ear with tones 200 msec long at the center frequencies of each critical band (with the exception of the lowest one). This audiogram could then be compared with the pattern of energy arriving at the ear, and a prediction of relative detectability could be made. Detection was predicted to occur when one critical band contained enough energy to exceed the auditory threshold as measured in the same critical band.

Selection of Test Sounds

The exact choice of sounds for use as stimuli in these experiments was dictated by both practical and theoretical considerations. A general class of sounds thought to be of very great practical significance was that associated with the immediate presence of enemy personnel, viz., sounds related to personnel movement, camp activity, personal combat equipment, etc. These are sounds that a

sentry, listening post or reconnaissance patrol would have to be able to detect in order to accomplish their mission. Failure to detect such sounds could have life and death significance in combat situations. Prior to this experiment, however, no measures of these sorts of sounds had been made in such a fashion that would allow their detectability to be analyzed. Therefore, it was necessary to record and analyze a set of sounds for use.

A variety of sounds were tape recorded on high quality equipment and from these 24 sounds were selected for use in the test. They were: footfalls on leaves, sand, coarse gravel, in a puddle, on twigs, and on dry grass; trimming branches with a machete; chopping with a machete; movement through a sapling thicket and a rasberry thicket (two sounds); an M16 magazine being inserted; an AK47 magazine being inserted under both anechoic and reverberant conditions; an M16 being cocked; a 1906 Springfield rifle bolt operating; a C-ration pack being opened; urination on the ground; the safety being released on an M16 and an AK47; the entrenching tool being used as a hoe and as a shovel in gravel soil; and walking in high grass. The tapes were edited and a 1.1 sec segment selected was spliced into a loop and re-recorded so the same sound could be presented continuously during the detection phase of the experiment.

Procedure

Both ears of 10 subjects were used in these tests. These ears were selected from those available within the Laboratory to provide a wide range of sensitivities. Because the purpose of the first part of this experiment was to validate a predictive scheme, no systematic attempt was made to test ears with 'classic Army proviles,' although several such ears were included in the sample. Rather, a wide variety of audiometric profiles were sought to permit a good test of the detection model. The testing was done monaurally with an earphone that had been compensated so that its frequency reesponse was flat from 100 to 16,000 Hz $\pm$ 1 dB as measured with bands of noise on an artificial ear. Listening tests were conducted inside a double-walled acoustic chamber.

The audiogram of each ear of each subject was determined in response to 23 tones spaced at critical band center frequencies (150 - 13,500 Hz) for signal durations of both 20 and 200 msec. The use of two durations provided a check on the actual amount of temporal integration although, in the data analysis discussed next, only the 200 msec data are reported. These measures were made by having the subject's response control a recording attenuator which allowed him to track his threshold of audibility (just as in standard audiometry). Examples of three audiograms, demonstrating the wide range of audiometric profiles tested in these experiments, are shown in Fig. 1.

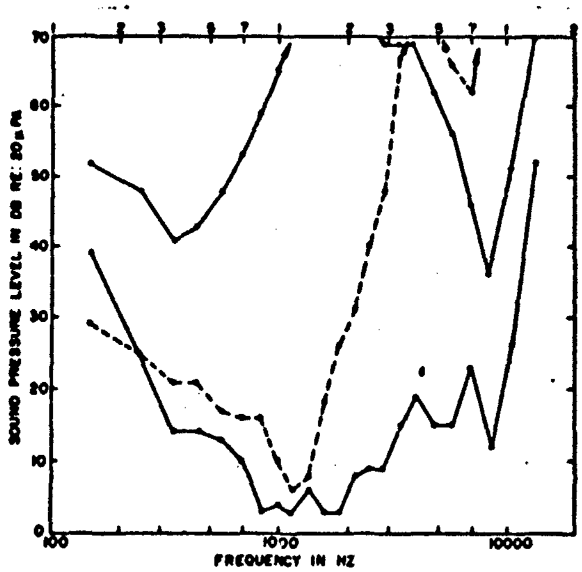

Figure 1. Sample audiograms illustrating the range of hearing sensitivity examined

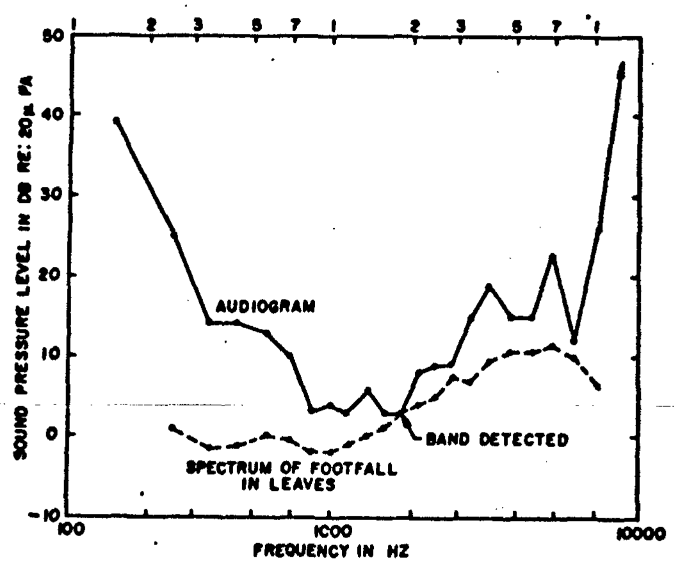

Figure 2. Superimposition of an audiogram and a sound spectrum, illustrating the determination of the band in which detection would occur

The lowest curve is typical of a young, normal ear. The dashed curve shows a loss at the high frequencies that is typical of ears that have been exposed to intense sound. The highest curve is of a most unusual sort, showing severe loss in the mid-range while retaining some sensitivity at both the high and low frequencies. After the thresholds for tonal stimuli were established, the tape-recorded sounds were substituted for the tones and the subjects tracked their thresholds for the combat-type sounds.

As discussed earlier, the pure tone thresholds were compared with the spectra of the complex sounds as analyzed by the computer program, and a prediction was generated with respect to both the critical band that would be detected and the attenuator setting at which it would occur. The process is illustrated in Fig. 2. (The actual comparisons were done graphically by plotting the spectrum on one sheet of graph paper and the threshold on another, superimposing them, and moving them until one of the bands of the spectrum met the audiometric curve.) In this case, the spectrum for a footfall on leaves first met the threshold of audibility in band 13 (1850 Hz center frequency). An arbitrary reference level on the audiometric curve was read with respect to the spectrum, and this represented the prediction for this particular combination of ear and sound. This prediction was then compared with the attenuator setting at which detection actually occurred. Once all the ears had been tested, a product-moment correlation coefficient was calculated for each sound.

RESULTS AND DISCUSSION

Spectra of the Test Sounds

Examples of the sound spectra, demonstrating the varying spectral shapes, are presented in Figs. 3 and 4. Figure 3 shows three spectra produced by the operation of equipment. The operation of a Springfield rifle bolt shows a spectral peak in the 4 - 8 kHz region, rising almost 20 dB from the lower frequencies. By contrast, the noise of trimming with a machete is relatively broad band and without any particular slope. The noise produced by the insertion of a magazine into an AK47 rifle shows a spectrum peaked in the mid-range at about 1200 Hz, and falling off almost 20 dB on either side. Figure 4 shows three sound spectra resulting from personnel movements in different settings. The footfall on gravel slopes from the low to the high frequencies, while the footfall on grass has most of its energy in the low and high frequencies and the least energy in the mid-range. Lastly, the footfall on leaves has most of its energy in the high frequencies, showing a peak at about 7 kHz. These spectra are presented to show the variety of shapes that are produced by sound of this type, and to give some idea of the differences one might expect to find in

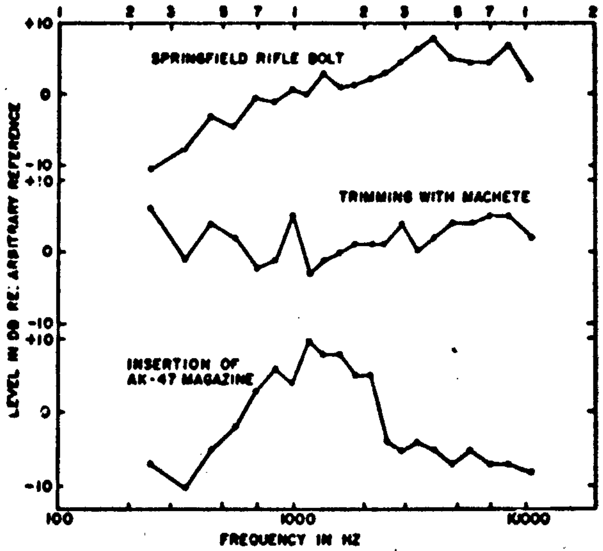

Figure 3. Examples of equipment sound spectra

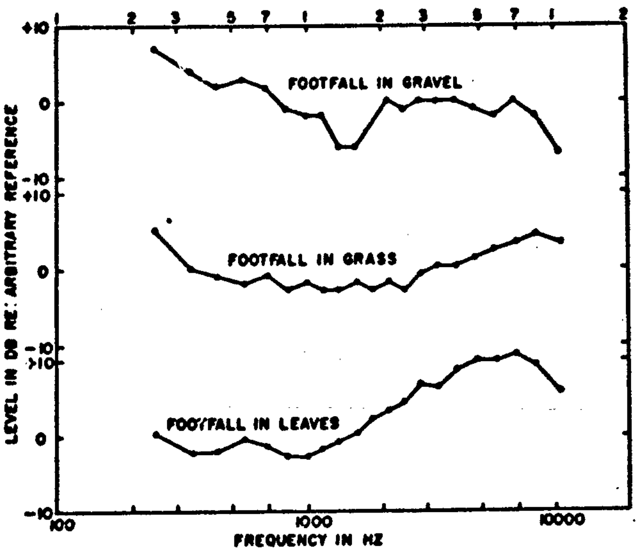

Figure 4. Examples of sound spectra of movement of personnel

the distribution of energy. The remaining spectra have been published elsewhere (Price & Hodge, 1976). The maximum difference between portions of the spectra processed as these were is about 20 dB; put another way, the range for most sounds was often considerably less than 20 dB. This will be important when we consider how it is that normal and impaired ears compare in their ability to detect these sounds.

With respect to temporal integration the data were in keeping with theoretical expectations. For example, for sounds that had most of their energy delivered in a short period (e.g., chopping noises) there was almost no difference between the spectrum derived for the peak 20 msec period and the one derived for the 200 msec maximum. For longer sounds (e.g., footfalls on leaves or grass), the amount of integration amounted to about 8 dB (the theoretical maximum being 10 dB).

Prediction of Detection

The correlation coefficients for the predicted and actual detection levels ranged from .89 to .98 with a mean for the 24 sounds of .94. Thus, about 88.4% of the variance was accounted for. The standard error of estimate (devialton from the regression line) ranged from 3.0 to 5.1 dB, and on the average was only 4.1 dB. This is quite small when one considers that the standard deviation for test-retest audiometric data is normally on the order of 5 dB. Thus, it can be concluded that the model predicts detectability exceedingly well, and that additional refinement could add almost nothing to its predictive capacity.

Applications to Operational Situations

The logical questions that arise at this point are how we might expect normal and impaired ears to compare in their ability to detect sounds, and how much difference hearing loss makes to performance in operational situations. We hasten to interject at this point that the final answer to these questions is still in the future; however, the present data, when coupled with what is now known about the hearing of soldiers in the combat arms, and the environments in which they might function, do result in some interesting conclusions.

We are fortunate in having some excellent data on the hearing levels of soldiers in the combat arms: armor, infantry and artillery (Walden, et al., 1975). In this cross-sectional survey, hearing levels of 3000 soldiers were measured following varying periods of service, and the hearing levels for average ears following varying periods of service were derived. Some of these data have been converted to absolute sound pressure level and are presented in the

upper three curves in Fig. 5. The upper curve (worst hearing) is that of the average man with 17.5 to 22.4 years of service; the center curve represents the weighted average for all ears in these combat arms; and the lower curve represents the average for the youngest ears (1.5 - 2.4 years of service). The bottom curve in Fig. 5 is the standard curve for audiometric zero, i.e., the hearing sensitivity expected of a young, normal ear.

These four curves were then used with the test sound spectra to derive predictions about detection. The young, normal ear would have detected sounds much sooner than the oldest Army ears—on the average about 16 dB sooner (range: 12 - 24 dB). The differences were, of course, smaller for the younger ears where the hearing losses were less severe. Given the relatively large hearing losses at the higher frequencies in the older ears, larger differences in detection might have been expected. The reason that they were not larger was that most of the detections were made on the basis of sound energy in the 1000 Hz frequency region where the ears did not differ much in sensitivity. Stated another way, the spectra of the sounds with the most high-frequency energy were not peaked enough at the high frequencies to allow the ears with relatively good high-frequency sensitivity to detect those frequencies <u>before</u> the energy at the lower frequencies crossed the threshold. For two reasons, which will be discussed in the next sections, it would be premature to draw any conclusions from these data with respect to the effect of hearing loss on performance.

The differences in detection just mentioned could have considerable practical significance except for one thing that was revealed by subsequent analysis. Namely, these detections were determined under very quiet listening conditions inside a specially-designed acoustic test chamber. If a war were ever fought in such a chamber, the data would apply with only minor qualifications! The real world, however, even at its quietest, has considerable noise present. If a sound is to be detected, then the energy present must not only exceed the absolute sensitivity of the auditory system, but it must also exceed the ambient noise level, or else it will be masked by the noise. Examples of typical outdoor ambient background noise spectra are presented in Fig. 6 (from Garinther, et al., 1975). For frequencies in the mid-range and below, the jungle is quietest, so long as there are no insect or animal sounds. If insect sounds are present there is a dramatic increase in the amount of high-frequency energy, so that the spectral curve rises at about 9 dB/octave between 700 Hz and 10 kHz. The background noise spectrum for rural France (late in the evening without machinery sounds) is almost the reverse of the previous curve, showing a spectrum that declines with increasing frequency.

To estimate the effect of these background noises on detection, the curves in Fig. 5 (representing the hearing of typical Army ears as well as young, normal ears) were combined with the background

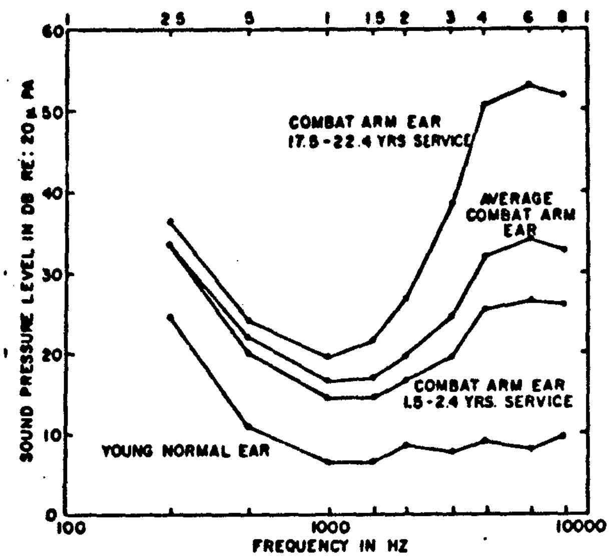

Figure 5. Hearing thresholds for representative Army ears and a young, normal ear (from Ref. 7)

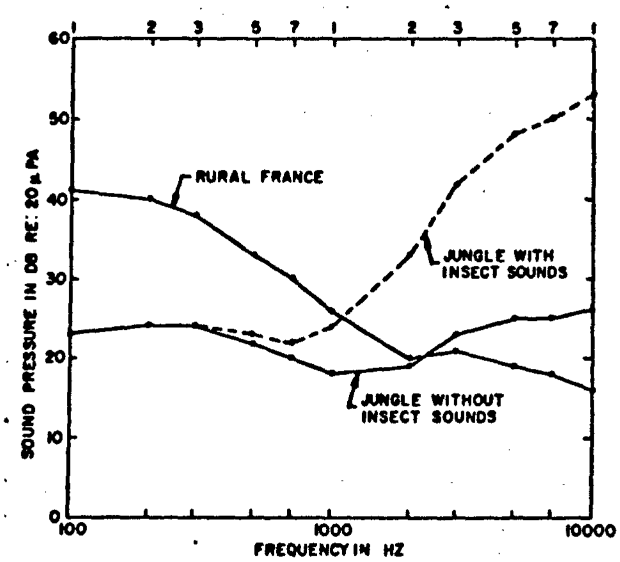

Figure 6. Background noise spectra (from Ref. 1)

noises; predictions of detectability were then redetermined for the set of 24 sounds used in these experiments. From these data it is apparent that the background noise exerts an overwhelming effect on detection, and that the differences between ears are therefore much smaller than when testing was done in the quiet. In the case of the jungle noise with insects and animals present, the predicted differences between the best and worst ears was only 0.3 dB on the average! In this case, almost all of the predicted detections occurred on the basis of energy in the low-frequency region where the ears were not very different in their sensitivities. The low-frequency masking noise also acted to equalize them by negating the superior sensitivity of the best ears.

The differences were not much greater for the jungle without insect noises, the predicted difference between the youngest and oldest Army ears being only 2.7 dB. In the spectrum present in rural France, however, the low-frequency content of the background noise was high enough that the detections tended to occur on the basis of energy present in the higher frequencies. In this case, the ears that had retained better high-frequency sensitivity were somewhat better able to detect. The young, normal ear did better than the old Army ear by 7.8 dB on the average, and the youngest combat arm ear did about 3.9 dB better than the oldest combat arm ear.

These differences, while not negligible, are nonetheless not very large and would, if taken alone, not seem to justify much concern for the preservation of hearing in our combat troops. In our opinion, however, this would be both a premature and an exceedingly dangerous conclusion to draw from these data. It will be recalled that the specific performance tested in these experiments was the ability to detect the presence of some sound exceeding background and/or physiological noise levels. At the outset this type of performance was defined as detection, and differentiated from 'identification.' Only as the intensity of a sound increases 20 dB or more beyond the detection level does the sound assume a quality where it sounds like something. In assessing performance in the field, it is this second level of analysis (i.e., identification) that is most important. At the moment, however, it is not possible to say just how much the intensity of sounds of the type we are concerned with must be increased above detection levels before identification can occur. Some preliminary data also suggest that this amount may be very different for normal ears and ears that have lost some sensitivity. Indeed, the most common complaint of an individual suffering from a hearing loss is not that he hears nothing but that he can't make sense out of what he does hear. The loss that an ear suffers appears, at a practical level, to be not so much one of sensitivity as one of analytical capability. This is clearly an important issue that needs to be

settled before any conclusion is drawn with respect to hearing sensitivity and performance in the field.

There are also a number of additional points that subsequent research should focus on in coming to grips with the importance of auditory input in operational situations. Signal detection theory, for example, suggests that a number of variables enter into the detection and identification process. Among them are the statistical distributions of both the physiological noise as well as the background noises. We do not know what these are for the types of sounds encountered in the field. Furthermore, the implications of making a detection are also known to influence the likelihood of making a correct detection as well as the likelihood of making a false alarm, i.e., if there are no negative consequences of making a positive response, the detections will be at their earliest but the false alarms will be greatest, and vice versa. The answers to these and other questions in this area are likely to have considerable significance for the Army in a variety of settings; therefore, we are presently conducting additional research to clarify the important interactions between the physical and psychological variables that operate when the human ear is used to detect and analyze combat-relevant sounds.

Summary and Conclusions

A comprehensive program of research has been initiated by the Human Engineering Laboratory to examine the hearing requirements of soldiers in a variety of operational contexts and to determine the effects of hearing loss on performance. The initial focus of this program is on the aural detection and identification of combat-relevant sounds, such as might enable soldiers to determine the presence and intentions of enemy personnel, and the initial experiments reported here relate to the factors involved in detecting sounds of personnel movement ~~and personnel activity.~~ One of the most important contributions of the present effort has been the development of a detection model which incorporates the ear's analysis of incoming energy into critical bands of frequencies, and its integration of energy arriving during a period of 200 msec. Based on these theoretical considerations a unique computer-based analysis procedure was developed, which was used to provide a prediction of the critical band(s) of primary importance in the detection of representative combat-relevant sounds.

Experiments were conducted using 20 ears representing differing degrees of threshold sensitivity, and encompassing the range usually observed for Army ears. Detection thresholds were obtained for tonal stimuli at the center frequencies of critical bands, for both 200 and 20 msec duration tones. Justaposition of the 200 msec tone audiograms with the spectral plots for the test sounds enabled

predictions to be made about the listening level at which detection would occur. The mean correlation coefficient between predicted and actual detection level was .94, which suggests that, considering known sources of variance in threshold testing, the detection model worked exceedingly well.

The results were used to make predictions about sound detection thresholds for representative Army ears, based on a recent survey of hearing sensitivity of personnel in the combat arms. This analysis showed that in the quiet predicted differences averaging 16 dB would exist between older Army ears and young, normal ears. However, when detections were predicted in the presence of typical background noises, the differences between ears were overshadowed by the masking effect of the background noise. These results apply to the detection of the simple presence of sound. The argument was advanced that the identification of sounds was more important for predicting performance in the Army context.

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